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Charmed baryons from lattice QCD

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Charmed baryons from lattice QCD

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The results of a recent quenched lattice QCD simulation for charmed baryons are presented. In contrast to a previous calculation, it is found that hyperfine splittings are in agreement with quark model expectations and comparable to experimental values. Preliminary calculations using lattice NRQCD yield results which are compatible with those obtained using a Dirac-Wilson action of the D234 type for the charm quark.

There have been many applications of lattice QCD to heavy-flavoured hadrons but most of the work has been restricted to the meson sector. The most complete study of heavy baryons in a relativistic framework is the one done in the UKQCD collaboration[1] using an $O(a)$ improved fermion action in quenched approximation. In that work the overall features of the baryon spectrum were found to be in agreement with experiment but hyperfine splittings in both charm and bottom baryons were found to be considerably smaller than those predicted by phenomenological models[2] and observed experimentally. In fact, the central values for hyperfine splittings found in [1] were negative. Such a result is difficult to understand and would pose a severe problem for lattice QCD. Therefore further investigation seems justified.

Due to limitations in computing resources it was not possible in this work to use the same lattice spacing and volume as used in the UKQCD calculation. Rather, a special strategy had to be adopted. We work on a more coarse lattice ($\sim 0.2\text{fm}$) with a highly improved action. Past experience has shown that results of reasonable accuracy may be obtained with such lattices[3]. In order to check the calculation, the spectrum of baryons in the light quark (u,d,s) sector was calculated at the same time. As well, meson masses for both heavy and light quarks were calculated. The results of all these calculations (see [4] for details) are in reasonable agreement with experimental values and with the results obtained at small lattice spacing[5,6].

The explicit form of the gluon and fermion action may be found in [4]. The fermion action is of the D234 type[7] with tadpole improvement implemented using the Landau link. The lattice was anisotropic with a bare aspect ratio a_s/a_t of 2. A total of 420 quenched configurations on a $10^3 \times 30$ lattice were analyzed.

The results for singly charmed baryons are given in Table 1. In contrast to [1] the hyperfine splittings are positive and large in magnitude. Figure 1 shows the mass difference $\Sigma_c^* - \Sigma_c$ as well as the results for the Σ -hyperon and nucleon - delta compared to experimental values. Also shown are the results of lattice calculations[5,6] done with different actions on lattices with much smaller lattice spacing than used here. The results of our simulation are seen to be quite compatible.

The masses of doubly charmed baryons have also been calculated. The results are 3.598(13)GeV and 3.682(20)GeV for Ξ_{cc} and Ξ_{cc}^* respectively. For Ω_{cc} and Ω_{cc}^* we get masses of 3.697(10)GeV and 3.775(12)GeV. The hyperfine splittings are only slightly smaller than for singly charmed baryons.

In lattice QCD masses are extracted from correlation functions of hadron operators. One difference between the present calculation and that of Ref.[1] is in the choice of baryon operators. In [1] calculations are done with interpolating operators of the form:

$$O_5 = \epsilon^{abc}(l_a^T C \gamma_5 l'_b) h_c, O_\mu = \epsilon^{abc}(l_a^T C \gamma_\mu l'_b) h_c \quad (1)$$

where l, l' are light quark fields and h is a heavy

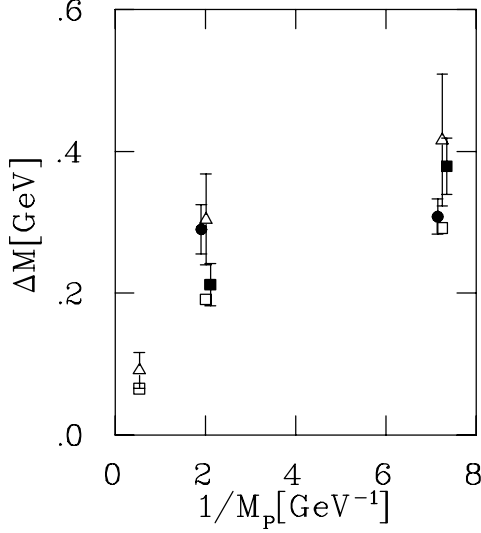


Figure 1. Spin splitting for baryons with different flavour versus inverse of the corresponding pseudoscalar meson mass. The open squares are experimental values and the triangles are the results of this work. For comparison the results of [5] (filled squares) and [6] (filled circles) are also shown.

Table 1
Masses of singly charmed baryons. Masses are given in GeV, mass differences are in MeV. The experimental values are taken from [8] except for Ξ'_c which is from [9]

	This work	UKQCD[1]	Experiment
Λ_c	2.304(39)	2.27^{+4}_{-3}	2.285(1)
Σ_c	2.465(22)	2.46^{+7}_{-3}	2.453(1)
Σ_c^*	2.557(30)	2.44^{+6}_{-4}	2.518(2)
Ξ_c	2.454(21)	2.41^{+3}_{-3}	2.468(2)
Ξ'_c	2.579(14)	2.51^{+6}_{-3}	2.575(3)
Ξ_c^*	2.672(16)	2.55^{+5}_{-4}	2.645(2)
Ω_c	2.664(12)	2.68^{+5}_{-4}	2.704(4)
Ω_c^*	2.757(14)	2.66^{+5}_{-3}	
$\Sigma_c^* - \Sigma_c$	91(25)	-17^{+12}_{-31}	65(2)
$\Xi_c^* - \Xi'_c$	94(13)	-20^{+12}_{-24}	70(4)
$\Omega_c^* - \Omega_c$	94(10)	-23^{+6}_{-14}	

field (for O_μ , l' may be the same flavour as l). This choice of operators is motivated by heavy quark symmetry where baryons are classified according to the total spin (0 or 1) of the light flavours.

Our approach is different. The aim is to do a unified analysis, incorporating all flavours (quark masses) in a common framework. We therefore start with the nucleon operator for which a common choice[10,11] is

$$\epsilon^{abc}(u_a^T C \gamma_5 d_b) u_c \quad (2)$$

where u and d are up and down quark fields. It can be shown that this operator contains the component

$$\epsilon^{abc}(u_a^T C \gamma_\mu u_b) \gamma_5 \gamma^\mu d_c \quad (3)$$

which is expected to survive in the limit where the mass of the unlike quark (d in this case) is taken to be very heavy. Therefore the familiar operators used in light baryon spectroscopy should also be applicable, with appropriate substitution of fields, in the heavy baryon sector. The forms used may be found in [4].

In principle, masses should be independent of the interpolating operators used as long as the quantum numbers are the same. In view of the difference between the results of the present calculation and Ref.[1] it is worthwhile to check if this independence of operator is obtained in practice. We have therefore analyzed a subset of our configurations using operators of the form (1) and compared the results with those obtained using the operators given in [4]. Typical comparisons are shown in figure 2. The quantity shown in the figure is $M(t) = \ln(G(t)/G(t+1))$ where $G(t)$ is the hadron correlator and for large times t it is equal to the mass. It is seen that the mass is indeed the same for the two different choices of interpolating operator.

In the continuum limit the D234 action describes Dirac fermions. For heavy quarks on the lattice, it can be advantageous to use a nonrelativistic approach[12]. For b-quarks this seems to work well but for charmed quarks it is less clear whether lattice NRQCD is adequate[13,14]. A particular concern is that hyperfine splittings in

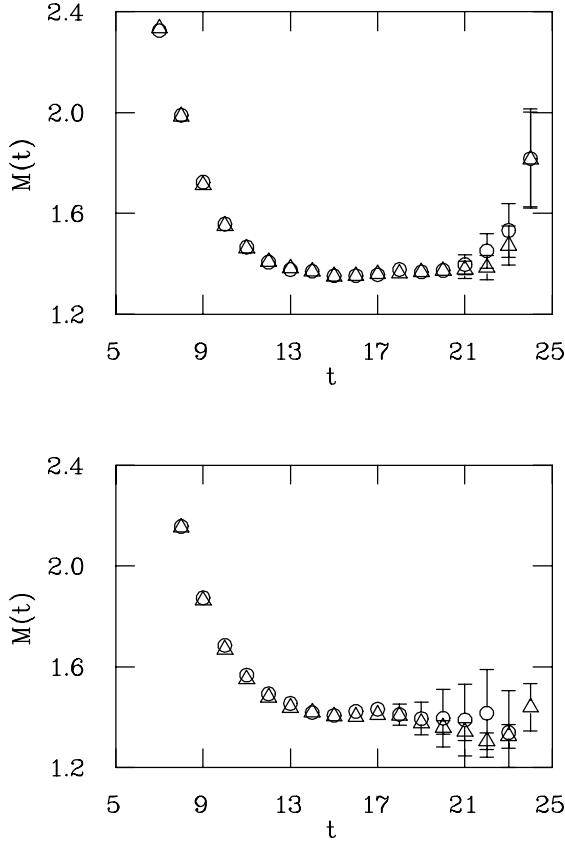


Figure 2. $M(t)$ calculated using two different baryon operators. The upper figure is for Ω_c and the lower is for Ω_c^* . The results using the operators (1) are shown by circles, those using the operators of [4] are shown by triangles.

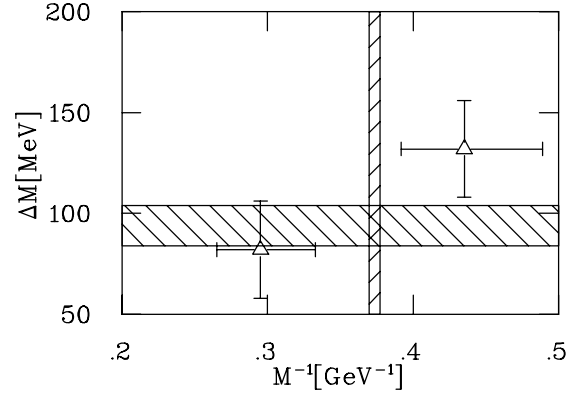


Figure 3. The mass difference ΔM for $\Omega_c^* - \Omega_c$ calculated using lattice NRQCD for the charmed quark. The intersection of the cross hatched bands indicates the result obtained with the D234 action.

the meson sector seem to be underestimated compared to experimental values[13–15]. Therefore it is of interest to investigate the baryon sector.

We have carried out a preliminary analysis of charmed baryons using lattice NRQCD, instead of the D234 action, for the charmed quark. The result for the mass difference $\Omega_c^* - \Omega_c$ is plotted in Figure 3 and for $\Omega_{cc}^* - \Omega_{cc}$ in Figure 4. For comparison, the results obtained using the D234 action for the charmed quark are also shown. Calculations were done for two different values of the nonrelativistic charm quark mass which should be tuned to reproduce the charmed baryon mass (indicated by the vertical cross hatched area in the figures). Interpolating between the two points calculated using NRQCD, one sees that the result for the spin splitting using NRQCD is compatible with that using the D234 (“relativistic”) action.

To summarize, we have calculated the spectrum of singly and doubly charmed baryons in quenched lattice QCD. In contrast to a previous calculation[1], it was found that hyperfine splittings are positive as expected, for example, from the quark model and are comparable in magnitude to experimental values. This result is quite robust. It is independent of the choice of inter-

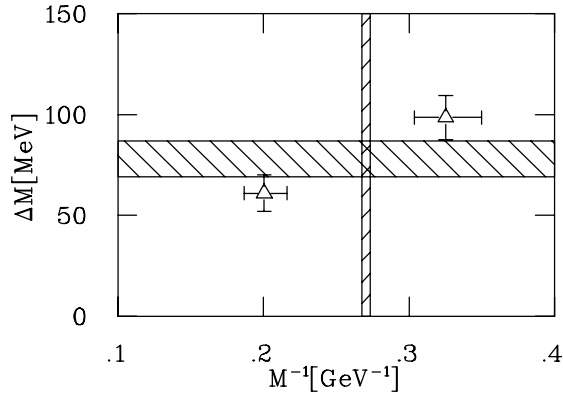


Figure 4. The mass difference ΔM for $\Omega_{cc}^* - \Omega_{cc}$ calculated using lattice NRQCD for the charmed quark. The intersection of the cross hatched bands indicates the result obtained with the D234 action.

polating operators for the baryons. Preliminary results also indicate that use of an NRQCD description for the charmed quark yields values for the spin splittings compatible with those obtained using the D234 action.

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